GEANT4 Photon Readout Simulations of Plastic Scintillating Strips with Embedded WLS Fibers

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***Abstract*— The study of ν_μ to ν_e oscillations using high intensity neutrino "super beams" is the most promising avenue for measuring neutrino oscillation parameters to an order of magnitude improvement in precision. The international J-PARC/SK proto-collaboration proposes to measure these parameters with the existing SuperKamiokande (SK) detector as the far detector and a high-rate, fine-grained detector of $\sim$ 200 tonnes, placed near the production target to provide measurements of the initial neutrino beam flux. The near detector is based on extruded plastic scintillator strips built into 5m by 5m layers and read out by wavelength shifter fibers (WLS) and photomultiplier tubes (PMT's). An R&D program in Canada aims to optimize this mature technology for the J-PARC/SK experiment and find improvements to the photon readout system. To guide this development and to further validate the optical photon functionality in GEANT4, we added 'wavelength shifting' to the catalog of processes available with the toolkit, and compared simulations with controlled test bench measurements. This paper gives a short explanation of the optical photon process implementations available in GEANT4 and reports the results of our specific comparison.**

***Index Terms*— scintillation, wavelength shifting fibers, GEANT4.**

I. Introduction

J-PARC/SK is a long baseline neutrino oscillation experiment with focus on precision measurements of neutrino oscillation parameters that will connect the new Japanese hadron facility, J-PARC near Tokai, with the 295km distant SuperKamiokande detector at the Kamioka mine [1]. The first stage of the project will have increased sensitivity in the search for the conversion of muon neutrinos to electron neutrinos. For measurements to occur, a detector must be placed relatively near the proton source in order to measure the neutrino spectrum as it is produced. The Canadian group proposes a 200 tonnes detector, 280m away, with a possible design of stacked scintillation strips with embedded wavelength shifting (WLS) fibers. A simulation study of this technology is being done to help finalize the design parameters.

A. Experimental Observations

WLS fibers are used in many high-energy particle physics experiments. They absorb light at one wavelength and re-emit light at a different wavelength and are used for several reasons. For one, they tend to decrease the self-absorption of the detector so that as much light reaches the PMTs as possible. WLS fibers are also used to match the emission spectrum of the detector with the input spectrum of the PMT. Again, this is to allow for maximum efficiency of the equipment.

In the early stages of the R&D of the detector, many tests were performed on WLS fibers to measure some of their properties. In particular, the first set of experiments focused on the attenuation lengths of the fibers. It was noticed that the fibers have two attenuation lengths. A GEANT4 based simulation was used to better understand the measurement through individual ray tracing.

B. GEANT4 Simulations

1) Optical Processes in GEANT4: In order to simulate the scintillating strips and the WLS fibers, it is necessary to take advantage of the optical processes available in GEANT4 [2]. A photon is considered optical if it's wavelength is much greater than that of the typical atomic spacing and in GEANT4, optical photons are a class of particles separate from high energy gamma rays. This allows processes to be attached to optical photons that arise from the wave-like nature of electromagnetic radiation.

The processes that are available are reflection and refraction at boundaries, bulk absorption and Rayleigh scattering. In each case, the optical properties of the medium are stored as entries in a properties table that is linked to the material. Furthermore, the properties can all be expressed as a function of the photon's momentum.

GEANT4 also has processes that create optical photons, such as the Cerenkov process, transition radiation and the scintillation process.

2) Attenuation Length Simulations: The fiber used in the simulations is based on the Kurarray Y11 double clad model. It has a diameter of 2.0mm with cladding thickness of 3% of the diameter. The indexes of refraction are 1.60, 1.49 and 1.42 for the core, the first and second layers of cladding, respectively.

In a first step of the simulation and to verify its correctness, one constant absorption length was attached to the fiber material. Photons were then shot straight down the fiber and the number of photons that reached the end of the fiber was counted as the photon source was moved to different positions along the fiber. The resulting data, shown in Figure [1], was fit with one exponential, producing, as expected, an attenuation length of the fiber with the same value of the absorption length that was used as the input. The next step was to see the effect on the attenuation length when photons are produced at an

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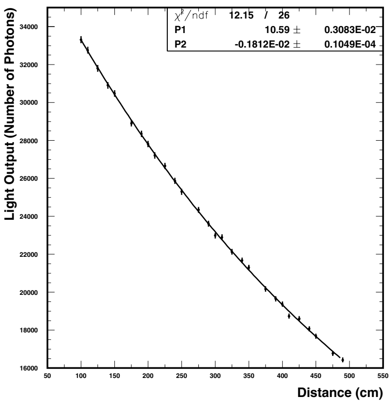

Fig. 1. Attenuation length simulation with one input absorption length.

angle with respect to the fiber axis. As shown in Figure [2], the attenuation length decreases as the opening angle of emission increases. This is due to the fact that the photons must travel a further distance within the fiber to reach the end. In reality, photons are created isotropically throughout the fiber and at all angles, thus the absorption length is greater than the attenuation length of the fibers. In the final step of the attenuation length

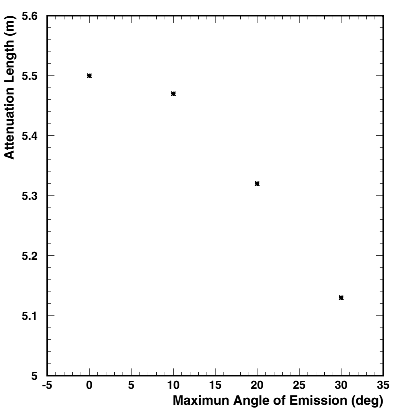

Fig. 2. Attenuation length of the fiber as emission angle (with respect to the fiber axis) of photons increases

simulations, the emission spectrum of the WLS fiber was input, along with two distinct absorption lengths for the two peaks of the emission spectrum. This models the overlap between the absorption and emission spectra of the WLS fibers. The resulting data is shown in Figure [3] and was fit with the sum of two exponentials. The result indicates that the two attenuation lengths of the fibers is due to the fact that there is some overlap between the absorption and emission spectra of the WLS fibers.

3) Scintillating Strips with Embedded WLS Fibers: In order to embed the WLS fibers into the scintillating strips, the wave-

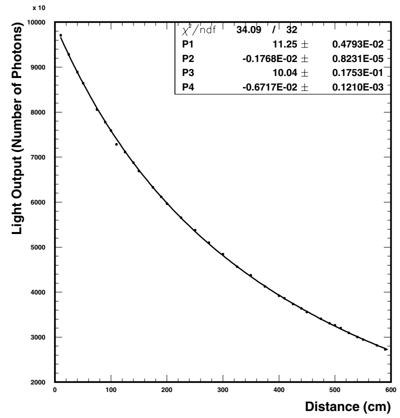

Fig. 3. Results for attenuation length simulations with input spectrum of WLS fiber.

length shifting process had to be implemented into GEANT4 as another optical process. The new functionality requires 3 inputs:

- WLSABSLENGTH is the absorption length of the fiber as function of the photon's momentum.
- WLSCOMPONENT is the emission spectrum of the fiber as function of the photon's momentum.
- WLSTIMECONSTANT accounts for any time delay which occurs between absorption and re-emission of the photon.

In the simulation, information such as the total number of scintillation photons produced, the total number of photons that reach the fiber and the total number of photons that reach the end of the fiber can be extracted from the program.

This information was used to investigate the effect of changing the number of fibers in each strip and also the effect of changing the position of the fibers within the strip.

Four simulations were performed in all. In the first case, the fiber is placed in the center of the 2cm $\times$ 2cm $\times$ 5m scintillating strip. In the second case, one fiber is placed at -0.5cm and one at 0.5cm along the x-axis. In the third case, one fiber was placed at -0.5cm, another fiber was placed in the center and a third fiber was placed at 0.5cm. In the last case, two fibers were situated next to each other in the center of the scintillating strip.

An electron was simulated traversing perpendicularly through the width of a scintillating strip, starting at different positions along the x-axis of the strip. The fraction of scintillation light that reached the fibers is shown in the Figure [4] as a function of the position of the entrance of the electron. It is obvious that as the number of fibers increases, so does the amount of light collected by the fibers. It can also be seen that the amount of light collected increases in regions where the electron passes through the scintillating strip near a fiber. This is most evident in the case were the two fibers are in the center of the strip. The amount of light collected by the fibers when the electron enters near the edges is much less then when the electron enters near the center.

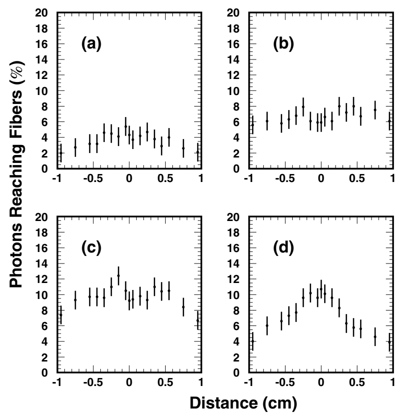

Fig. 4. Effects of different number of fibers per strip. (a) One fiber placed in the center of the strip. (b) Two fibers; one fiber placed at -0.5cm and one fiber placed at 0.5cm along the x-axis. (c) Three fibers; one fiber placed at -0.5cm, one fiber placed at 0.0cm and one fiber placed at 0.5cm along the x-axis. (d) Two fibers; placed next to each other at the center of the strip

II. Conclusion

As part of the J-PARC-Kamioka collaboration, the Canadian group is performing research and development into the 280m near detector. A possible design is based on extruded scintillator strips with embedded wavelength shifting fibers.

The observation of two attenuation lengths guided the simulations performed with GEANT4. Two apparent attenuation lengths were also obtained with the simulations and are due to the overlap between the absorption and emission spectra of the WLS fibers.

The wavelength shifting process was implemented as a new optical process in GEANT4 in order to study the embedded fibers. Using the embedded fibers, simulations were performed to see the effect of changing the number of fibers in a scintillating strip. This allowed a profile of light collected by the fibers to be created.

The power of GEANT4 lies in the ability to adapt the detector geometry without physically building the different scenarios. Eventually, the entire detector will be simulated using GEANT4 in order to finalize the physical parameters.

References

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